## 3.5. Coupled Global Positioning System/Inertial Navigation System

### 3.5.1. General

The Global Positioning System (GPS) was designed to provide an unlimited number of users with continuous, worldwide, all-weather, common grid, three-dimensional, positional information as well as a highly accurate source of time and doppler based velocity information. GPS consists of the three segments: [Ref. 48:p. I-3, I-4].

- ✓ Space Segment
- ✓ Control Segment
- ✓ User Segment[10]

### 3.5.2. Space Segment

The space segment consists of a constellation of 18 operational satellites with three on-orbit spares. The satellites are spaced in six planes inclined at 55° with three or four satellites per plane. The satellites travel in 10,900 nm circular orbits with a period of twelve hours. Each satellite transmits a continuous information stream including its own satellite ephemeral data[11], atmospheric propagation correction data and satellite clock bias information. The data are transmitted on two frequencies, 1575.42 MHZ and 1227.6 MHZ, known as L1 and L2, respectively. Two frequencies are used so that an algorithm can be applied to correct ionospheric propagation effects. [Ref. 10].

### 3.5.3. Control Segment

The Control Segment consists of five Monitor Stations, three Uplink Stations and a single Master Control Station as depicted in figure 10. The Monitor Stations passively track each satellite within their view and collect ranging data using the satellite signal. The information is passed to the Master Control Station in Colorado Springs, Colorado, where updated satellite ephemeral data, clock bias and ionospheric propagation corrections are calculated. These new parameters, unique to each satellite, are then uplinked to the constellation via the three Uplink Stations. The Control Segment uses a frequency of 2227.5 MHZ for downlink from the satellite and 1783.74 MHZ for uplink to the satellite. [Ref. 48:p. I-6, Ref. 11].

### 3.5.4. User Segment

The User Segment consists of the various GPS equipment carried onboard the user platforms. GPS equipment may be carried on ground vehicles, ships, by individual persons and on aircraft. This document will concentrate on the testing of aircraft-based user equipment.

A typical aircraft installation includes an antenna and associated cabling/coax, a receiver, which converts the incoming RF signals to digital messages, a processor unit and a display. The receiver and processor are often contained within the same physical unit or may be placed on a single card for inclusion in another unit.

The receiver and processor accept the satellite ephemeral data and use it to calculate a precise location for the satellite. The satellite sends the exact time of transmission of each message. The processor uses the exact time of transmission and reception of the signal, corrects the signal, scales the difference in time by the propagation rate, corrects ionospheric propagation effects and thus calculates the unambiguous range to the satellite. Knowledge of the satellite location at the time of transmission thus provides a sphere on which the user equipment antenna must be located. By performing the same calculations for three satellites, an unambiguous position upon the surface of the earth is calculated. By adding a fourth satellite's information, a three-dimensional position is provided. [Ref. 10].

[10]This document will discuss the testing of airborne user equipment only. It is assumed that the space and control segments are fully developed and their performance quantified.

[11]Ephemeral data include a complete description of the orbital parameters of the satellite and thus allow the calculation of the precise location of the satellite at any time.

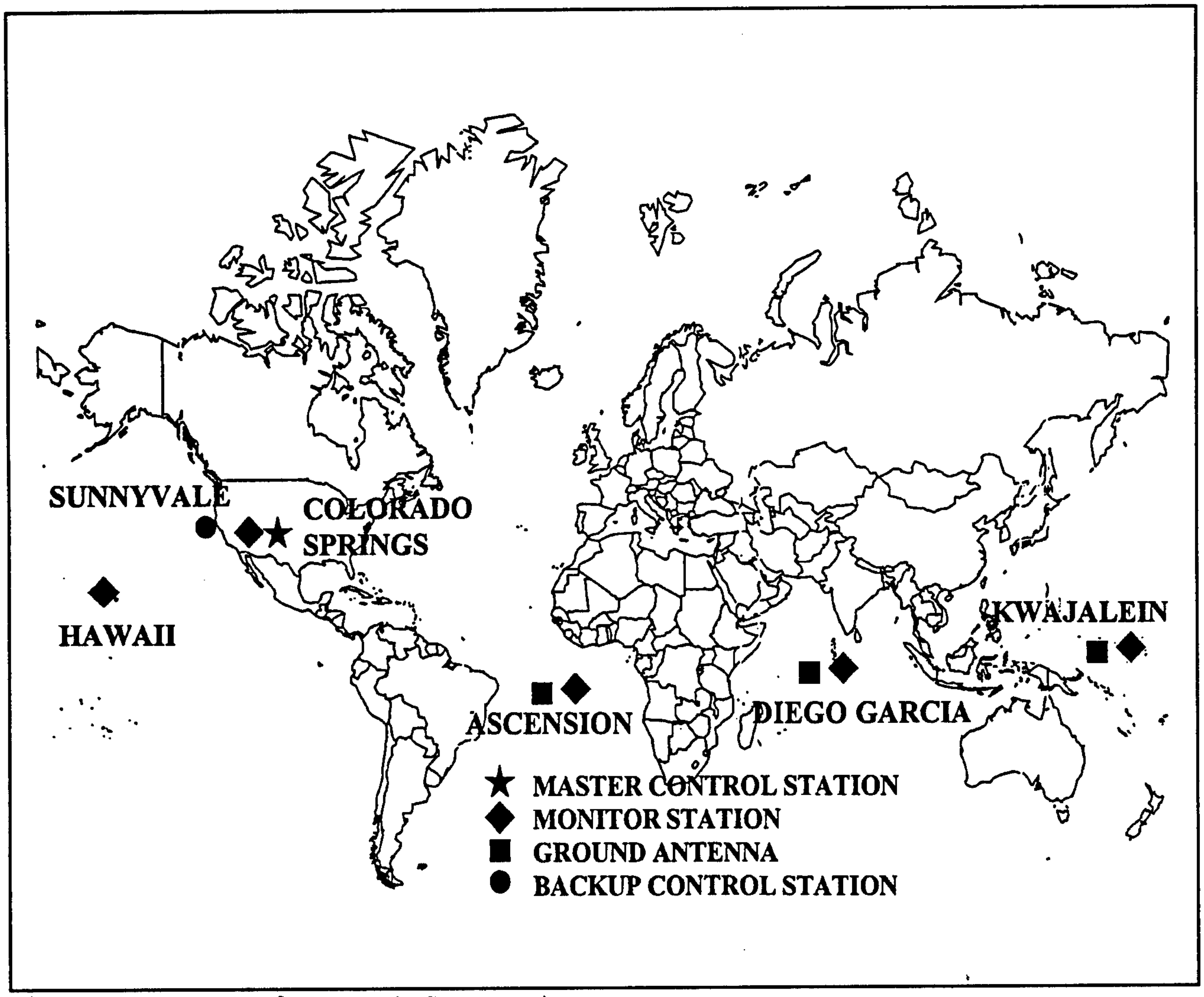


**Figure 10:** Control Segment Components

For airborne applications, the receiver/processor is designed to simultaneously receive, decode and use the signals from four to eleven different satellites simultaneously. In this way, the required signals for three-dimensional position calculations can always be tracked even when satellites rise and fall from view.

In addition to range, the ephemeral data, aircraft location and doppler shift of the GPS signal are used to calculate platform translation velocities. A very precise time source is also available from the GPS system. [Ref. 10]. The GPS concept is graphically depicted in figure 11.

## 3.5.5. Selective Availability

The GPS-generated position is typically very accurate. It is so accurate that its position is adequate for targeting of many weapons. During the design of the GPS system, it was the stated intent of the U. S. DoD not to make targeting grade accuracy available to everyone. The GPS signal is thus degraded somewhat, requiring special cryptographic equipment to attain the full system accuracy. This function is called the Selective Availability (SA) system. To obtain the SA accuracies, cryptographic hardware and a special code, called the P code, which is periodically changed, must be loaded.

## 3.5.6. Accuracies

The GPS, with SA applied, is designed to provide 16 m Spherical Error Probable (SEP) accuracy. SEP is a sphere with radius equal to the 50% error bounds. A sphere is used vice a circle since the GPS is capable of three-dimensional positioning. Without SA applied, the GPS

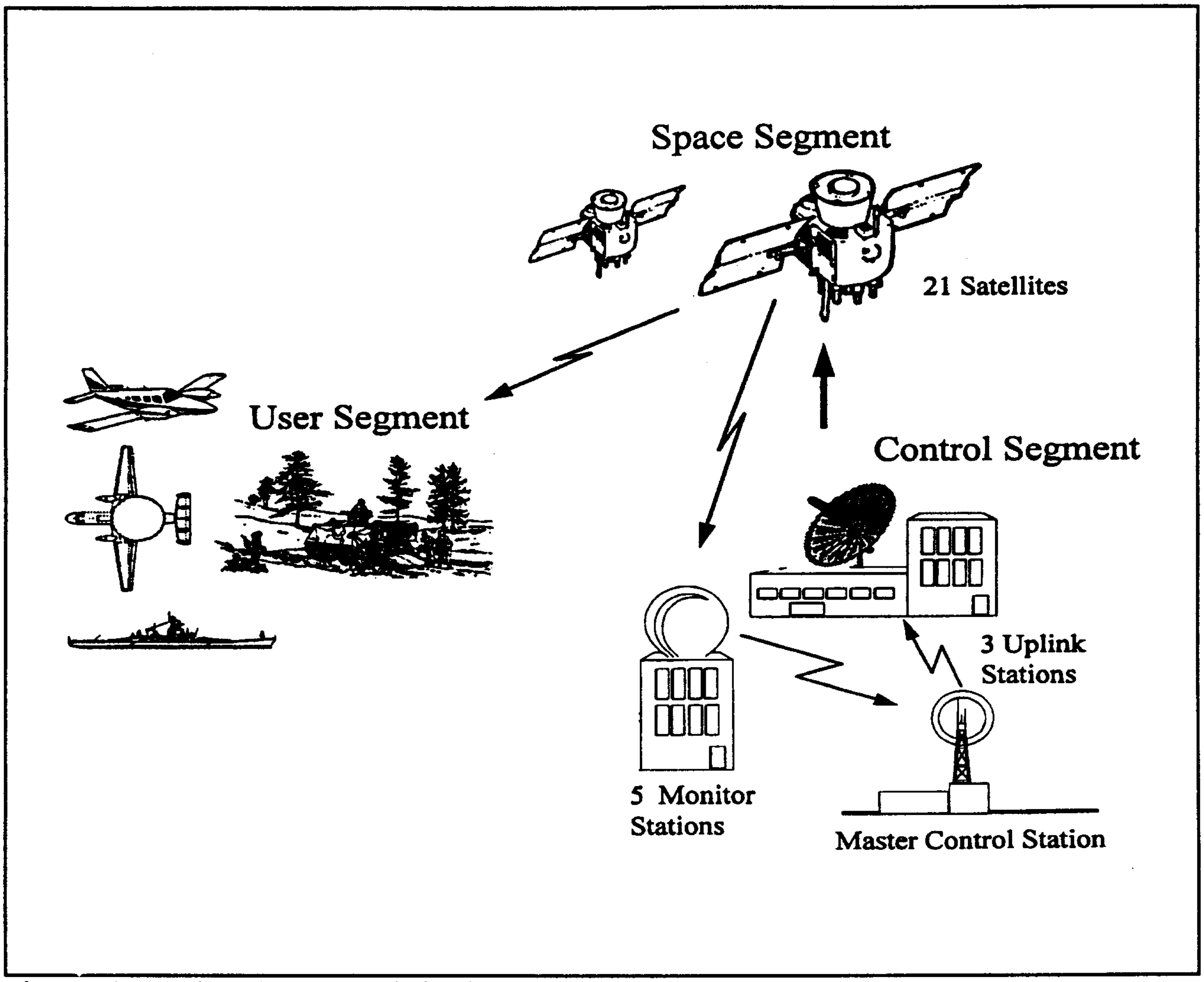


**Figure 11:** The Global Positioning System Concept

is designed to provide 100 m SEP accuracies. It is important to note that the non-SA accuracy is completely arbitrary and totally dependent upon the desires of the satellite controllers. [Ref. 48:p. I-10]. GPS time is typically accurate to 100 nanoseconds and velocity to 0.1 m/sec. [Ref. 10].

GPS user equipment performance is affected by seven factors [Ref. 10]:

- ✓Vehicle Dynamics
- ✓Multipath Effects
- ✓Nominal System Errors
- ✓Vehicle Environment
- ✓Satellite Constellation Geometry
- ✓Ionospheric/Tropospheric Effects
- ✓Hostile Environment

These test procedures will specifically isolate and quantify vehicle dynamics and multipath effects. Since these tests are performed on the GPS, as installed in the aircraft, the nominal system errors and errors due to the vehicle environment will be indistinguishable and will be quantified as a group. To date, a full constellation of GPS satellites are airborne and thus, an adequate set of satellites should always be visible. If problems are noted during the test, it may become necessary to either isolate or eliminate the geometry effects. This is readily accomplished since the satellite ephemeral data are openly available. A number of software programs are available for accomplishing this task. As an example, the author was provided, free of charge, with a set of GPS simulation and utility programs which included algorithms for calculating GPS satellite visibility as well as GDOP predictions [Ref. 51: p 3]. As long as the system does not exhibit deficiencies during the tests to be described, it will not be necessary to check for satellite constellation geometry problems. Ionospheric/tropospheric effects are corrected within the space segment. For the purposes of this test, it will be assumed that the space segment corrections are functioning appropriately. The user equipment hostile environment includes the effects of hostile jamming of the satellite signal. The effects of intentional, hostile jamming will not be considered in this document.

## 3.5.7. Precise Space Positioning Instrumentation

Due to the extreme accuracy of the GPS system, GPS testing requires an instrumentation system which is also extremely precise. Target location must be known to at least the accuracy to which the tester is attempting to validate the system. Two classes of trackers are usually used to obtain accuracies on the order of a few feet, laser trackers and theodolite trackers.

Laser-based trackers are highly precise, but are severely limited in range. The limited range is exacerbated by high humidity or the presence of any visible moisture. Typically, the technique is no longer useful when the aircraft is greater than 15 nm from the laser. Most laser trackers provide both a precise bearing to the target as well as range. Ranging is done by pulsing the laser energy in a fashion similar to radar. Given a surveyed location of the laser tracker, the azimuth and elevation of the laser beam and the target range, the target latitude and longitude is calculated. Accuracies on the order of two to three feet are typical. With accuracies less than the dimensions of the aircraft, it is necessary to specify the location on the aircraft which is to be tracked. This is usually done by installing a small array of mirrors in the form of a hemisphere, on the aircraft. The laser then tracks this set of mirrors.

Highly accurate positioning may also be derived using a network of theodolite trackers. Conceptually, a theodolite is merely a telescope. The telescope is mounted on a precisely surveyed location. An operator places optical crosshairs over a chosen location on the aircraft. The precise azimuth and elevation angle of the telescope apparatus is then measured and thus a precise, three-dimensional line through the target location is known. The theodolites are used in arrays with several simultaneously providing lines of bearing, thus defining the location of the target. The maximum useful range is restricted by any condition which may affect optical visibility as well as by the geometry within the theodolite array. Accuracy is a function of the range from each theodolite and geometry with the best accuracy occurring when the lines of bearing from each theodolite used are approximately at right angles. Typical arrays allow coverage of a 15 to 20 nm area.

Most test ranges use the precise space positioning data as an input to a computer algorithm which then is used to calculate precise groundspeed and course. The calculations may be done off-line or in real time. For the purposes of developing the sample test techniques, it will be assumed that the calculations are performed real time and available to the test aircraft while the test is being performed.

Since the GPS position and the range derived space positioning data tend to be so accurate, it is absolutely necessary for the positions derived from both sources to use a common geodetic grid system and reference point. Until recently, the errors induced by shifting from one system to another were typically small enough that they were not significant relative to the system errors. With the advent of systems like GPS, the geodetic system differences can cause significant apparent errors in the GPS under test, when in fact, none exist. A geodetic set, common to the system under test, must be used, or corrections for the differences must be made during data reduction.

## 3.5.8. Sample System

The procedures to follow will be developed to test a sample system which includes an antenna mounted upon the top of a tactical aircraft, behind the cockpit. The receiver and processor are a single box internal to the aircraft. The positions, velocities and time, generated by the GPS, are passed to a second processor which integrates the GPS navigation information with the output of the aircraft INS described earlier. The GPS thus provides a continuous update to the INS position as well as an additional source of velocities. These inputs are combined with the INS solution using standard filters to produce a single navigation solution. This solution is more accurate than either the stand-alone INS or GPS is capable of developing.

In most cases, a Kalman filter is used in the GPS to develop the smoothed positions and in the INS to observe the platform rates, which are then used in the DR solution. The sample system uses a single, 18-state Kalman filter, combining the inputs of both. This arrangement has the advantage of exploiting the benefits inherent in both a highly precise position fixing system and a DR system. However, it also has the disadvantage that it retains the problems inherent in both systems. Therefore, it is necessary to test the system for all the weaknesses discussed in the INS testing section as well as the new problem areas inherent in the GPS system.

If either the GPS or INS inputs are not available, the algorithm continues to produce a navigation solution using the single source of information. The missing information is calculated as needed. The outputs to the operator are similar; however, the accuracies are limited to approximately that of the stand-alone INS or GPS as applicable.

The GPS/INS integration described here is an example of a coupled position fixing/DR system. It will be seen that the test techniques are logically a combination of those used for the sample INS and OMEGA systems used as the examples of pure position fixing and DR systems. The Preflight and Built-In Tests, and the Controls and Displays tests provided in section 3.2 are applicable as written to the sample GPS/INS.

## 3.6. GLOBAL POSITIONING SYSTEM TEST TECHNIQUES

### 3.6.1. Initialization and Alignment

#### 3.6.1.1. Purpose

The purpose of this test is to assess the coupled GPS/INS initialization and alignment procedures for their utility for quickly reaching full navigation status, with a minimum of operator time and attention, and the effect that these procedures have upon the set-up sequence of other aircraft systems.

#### 3.6.1.2 General

Since the GPS/INS used for the sample unit is a coupled system, several different configurations must be tested:

1. Fully coupled INS with GPS, initial latitude and longitude provided, P Code installed, on the ground.
2. GPS alone, initial latitude and longitude provided, P Code installed, on the ground.
3. GPS alone, initial latitude and longitude not known, P Code installed, on the ground.
4. Repeat 1 through 3 with the P code not installed.
5. INS alone.
6. Repeat 1 through 5 using an airborne alignment.

Initialization of the GPS requires two phases. In the first phase, synchronization of the GPS user equipment clock with satellite time is performed. In the second phase, the signal from each satellite is acquired, tracked and decoded to calculate a navigation solution. The initialization process typically takes several minutes to perform.

Initialization indications usually include a graphical display as the first satellite and each subsequent satellite signal is acquired. A quality number is provided as the signal for each satellite is decoded. Usually, the display of the first satellite coincides with the completion of the clock synchronization. The quality numbers will typically vary as the quality of the satellite signal changes, such as may occur as the satellite leaves the visible horizon. A separate quality number is usually provided which indicates the state of the complete GPS navigation solution. This number may be in terms of a confidence level with little physical significance or may directly relate to the expected positional accuracy. A discrete is usually provided which indicates that the system is providing the expected navigational accuracy. This will be considered the completion of the initialization phase for the sample system. [Ref. 10].

As the GPS begins the initialization process, it uses the user-entered or previously stored GPS location, approximate time and the stored library of satellite ephemeral data to determine which satellites are within view and which provide the optimal geometry for the navigation calculations. GDOP IS as important to GPS as it is for OMEGA. If the location is significantly incorrect, the initialization takes longer since